

CONSTRAINTS TO THE MASSES OF BROWN DWARF CANDIDATES FROM THE LITHIUM TEST¹

Eduardo L. Martín and Rafael Rebolo

Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain

e-mail addresses: ege@iac.es and rrl@iac.es

Antonio Magazzù

Osservatorio Astrofisico di Catania, Città Universitaria, I-95125 Catania,

Italy

e-mail address: antonio@ct.astro.it

Send offprint requests to: Eduardo L. Martín

¹Based on observations made with the William Herschel Telescope, operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, and on data collected at the European Southern Observatory, La Silla, Chile.

ABSTRACT

We present intermediate dispersion ($0.7\text{--}2.2 \text{ \AA pix}^{-1}$) optical spectroscopic observations aimed at applying the “Lithium Test” to a sample of ten brown dwarf candidates located in the general field, two in young open clusters, and two in close binaries. We find evidence for strong Li depletion in all of them, and thus infer lower mass limits of $0.065 M_{\odot}$, depending only slightly ($\pm 0.005 M_{\odot}$) on the interior models. None of the field brown dwarf candidates in our sample appears to be a very young (age $< 10^8$ yr) substellar object. For one of the faintest proper motion Pleiades members known (V=20.7) the Li test implies a mass greater than $\sim 0.08 M_{\odot}$, and therefore it is not a brown dwarf. From our spectra we estimate spectral types for some objects and present measurements of H_{α} emission strengths and radial velocities. Finally, we compare the positions in the H-R diagram of our sample of brown dwarf candidates with the theoretical region where Li is expected to be preserved (Substellar Lithium Region). We find that certain combinations of temperature calibrations and evolutionary tracks are consistent with the constraints imposed by the observed Li depletion in brown dwarf candidates, while others are not.

Subject headings: stars: low mass, brown dwarfs, lithium, spectroscopy – binaries: individual (Gl 623, LHS 1047)

1. INTRODUCTION

We have proposed that the search for Li in brown dwarf (BD) candidates can provide a definitive proof of their substellar nature (Rebolo 1991; Magazzù, Martín & Rebolo 1991, 1993; Rebolo, Martín & Magazzù 1992). Theoretical calculations show that BDs with masses below $0.07 M_{\odot}$ preserve a significant fraction of their initial Li content, while more massive BDs efficiently destroy Li at ages older than about 10^8 yr. For higher masses, above the substellar mass limit, total Li depletion occurs in shorter timescales (Magazzù et al. 1993; Nelson, Rappaport & Chiang 1993; Bessell & Stringfellow 1993; D’Antona & Mazzitelli 1994).

Many BD candidates have been discovered in the last few years, and it seems that any dwarf with spectral type later than about M6.5 could actually have a substellar mass (Kirkpatrick & McCarthy 1994), depending on its age. Isolated field candidates have uncertain mass estimates based on their position in the H-R diagram, and on comparison with theoretical evolutionary tracks. Candidates in binaries have dynamical constraints on their masses, and can potentially provide a more reliable proof of a substellar status. However, the uncertainties in the models and in the binary parameters have so far prevented a definitive confirmation of a brown dwarf. The search for Li is an independent tool for probing the masses of BD candidates. Rebolo et al. (1992) coined the term “Lithium test” to the use of Li as a discriminant between very low mass stars and brown dwarfs. The first results of its application on a small sample of candidates were reported by Magazzù et al. (1993).

In this paper we present the results of a Li search in a wide sample of BD candidates, ranging from proper motion members of the young open clusters Pleiades and Hyades to some of the coolest and intrinsically faintest field dwarfs. Preliminary results of this work are presented in Rebolo, Martín & Magazzù (1994). This paper is organized as follows: Section 2 describes the spectroscopic observations. Section 3 deals with the analysis of the data, including measurements of H_{α} in emission, radial velocities and upper limits to LiI equivalent widths. Finally, in Section 4 we infer lower limits to the masses of 14 BD candidates from the observed Li depletions, and we discuss the implications to current modelling and understanding of the substellar regime.

2. OBSERVATIONS

Table 1: Log of Spectroscopic Observations

Name	V	I	Tel.	t_{exp} (s)	Disp. (\AA pix^{-1})	Epoch	Ref.
GL 623 AB	10.3	8.0	WHT	330	0.7	Aug 6, 1992	1
LHS 1047 AB	11.5	8.7	WHT	300	0.7	Aug 6, 1992	2
HHJ 10 (PP1 10)	20.7	17.1	WHT	8400	1.5	Jan 20, 1993	3
LkCa 21	13.5	11.1	WHT	300	1.5	Jan 21, 1993	4
V927 Tau	14.3	11.2	WHT	400	1.5	Jan 21, 1993	4
BHJ 358		15.7	WHT	3600	1.5	Jan 21, 1993	5
LHS 2065	18.7	14.5	WHT	3600	1.5	Jan 21-22, 1993	6
LHS 2243	19.3:		WHT	3600	1.5	Jan 21, 1993	7
LHS 2924	19.7	15.3	WHT	3600	1.5	Jan 21, 1993	6
LHS 248 (GJ 1111)	14.8	10.5	WHT	1100	1.5	Jan 21, 1993	1
CTI 115638.4+280000	20.4	16.7	WHT	7200	1.5	Jan 22, 1993	8
ESO 207-61	20.4	16.2	ESO	7200	2.2	May 18, 1993	6
LHS 2397a	19.6	14.9	ESO	5400	2.2	May 18, 1993	6
Sz 81	15.6		ESO	120	2.2	May 18, 1993	4
TVLM 513-46546		15.1	ESO	4800	2.2	May 18, 1993	9
TVLM 868-110639		15.8	ESO	4800	2.2	May 18, 1993	9
GL 644 C (VB 8)	16.8	12.2	ESO	2600	2.2	May 18, 1993	1

References for V and I: 1. Leggett 1992; 2. Ianna et al. 1988; 3. Stauffer et al. 1994; 4. Herbig & Bell 1988; 5. Bryja et al. 1994; 6. Ianna 1993; 7. Kirkpatrick 1994 (private communication); 8. Kirkpatrick et al. 1994; 9. Tinney et al. 1993.

Spectroscopic observations have been carried out on one night in August 1992 and during two nights on January 1993 at the 4.2 m William Herschel Telescope (WHT), located at the Observatory del Roque de los Muchachos on the island of La Palma, and on one night in May 1993 at the 3.6 m telescope of the ESO La Silla Observatory. The observing log is shown in Table 1, in which the objects are listed by chronological order of the observations. The instrumentation used was the ISIS double arm spectrograph on the WHT, and EFOSC 1 at ESO. The nominal dispersions obtained with each instrument are also listed in the Table, and the slit projection was typically 2 pixels. We obtained the following spectral coverages: for the stars observed with ISIS on August 1992, $\lambda\lambda 6370\text{--}7270$; for the stars observed with ISIS on January 1993, $\lambda\lambda 5530\text{--}6970$ (blue arm), $\lambda\lambda 7860\text{--}8760$ (red arm); and for the stars observed with EFOSC 1 four orders were recorded simultaneously, giving $\lambda\lambda 6060\text{--}7030$, $\lambda\lambda 6780\text{--}7910$, $\lambda\lambda 7720\text{--}9010$, and $\lambda\lambda 8230\text{--}10340$.

The sample consists of the following objects: HHJ 10, a BD candidate in the Pleiades cluster, first found in the photometric survey of Stauffer et al. (1989, their object number 10) and confirmed as a proper motion member by Hambly, Hawkins & Jameson (1993); BHJ 358, the faintest BD candidate proper motion member of the Hyades in the sample of Bryja, Humphreys & Jones (1994); ESO 207-61, the Hyad moving group candidate discovered by Ruiz, Takamiya & Roth (1991); four of the coolest high proper motion dwarfs known in the Luyten (1979) LHS catalogue; CTI 115638.4+280000 (hereafter CTI 1156+28), a very cool field dwarf from Kirkpatrick et al. (1994); two TVLM very low-luminosity dwarfs from Tinney, Mould & Reid (1993); LHS 248 and GL 644 C, two benchmarks of cool dwarfs; two binary systems with BD candidate secondaries (GL623 and LHS1047); and finally three of the latest M-type T Tauri stars in the Herbig & Bell (1988) catalogue.

Each individual spectrum was reduced by a standard procedure using IRAF², which included debias, flat field, optimal extraction and wavelength calibration using arc lamps. The WHT spectra were finally flux calibrated using the standard stars Hz 15, Feige 25, Feige 98 and HD 19445, which have absolute flux data files available in the IRAF environment. In Figures 1 and 2 we present the final spectra of ten programme

²IRAF is distributed by the National Optical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

objects, which are considered to be representative of the whole sample.

3. ANALYSIS

The spectral coverage of our data is large enough to estimate spectral types for those stars in our sample for which there was no classification in the literature. Only the two close binaries Gl 623 and LHS 1047, observed at higher resolution, do not have sufficiently large wavelength range, and hence they are left out from the analysis of spectral types. On the other hand, our relatively high dispersion allow us to measure H_α emission strengths and radial velocities. The spectral types, H_α equivalent widths and radial velocities are useful for interpreting the results of the Li search.

a) Spectral Types

Martín (1993) studied different spectral indexes that can be measured in our spectra, including those of Kirkpatrick, Henry & McCarthy (1991) and Prosser, Stauffer & Kraft (1991). He defined the following index:

$$M = \frac{F_\lambda(\lambda 8155 - \lambda 8175)}{F_\lambda(\lambda 7875 - \lambda 7895)}$$

where the F_λ s are the average fluxes over these 20 Å wide wavelength intervals. The M-index provides a smooth second order polynomial correlation with spectral type in the range M3-M9, the rms being less than half a spectral subclass. The referee (J.D. Kirkpatrick) has noted that there is a telluric water band between $\lambda 8164$ and $\lambda 8177$, and a strong VO bandhead coming in around $\lambda 7880$. We have not attempted to correct our spectra from telluric lines, but these were not conspicuous in any of the stars observed. We estimate that the contribution of telluric lines to the M-index in our spectra was less than 5% . We believe that the M-index is mainly sensitive to the slope of the pseudo-continuum and the strength of VO absorption. Our spectra in the spectral region where the M-index is defined can be seen in Martín (1993). For calibrating this index we used programme stars with spectral types listed in Herbig & Bell (1988) and Kirkpatrick et al. (1991, 1994); namely, LkCa 21 (M3), V927 Tau (M5.5), CTI 1156+28 (M7), GL 644 C (M7), LHS 2397a (M8), LHS 2243 (M8), LHS 2924 (M9) and LHS 2065 (M9). In Table 2 we present the spectral types obtained for the rest of our sample.

b) H_α and radial velocities

All our spectra include H_α , which is seen in emission in most programme stars (see for example Figures 1 and 2). Our moderately high spectral resolution has allowed us to detect weak H_α emission in several very cool field dwarfs, including LHS 2924. The measured equivalent widths of H_α emission are presented in Table 2. The strength of H_α could be an age indicator, as it seems to decay from the Pleiades to the Hyades, and from these to the field dwarfs for spectral types M0-M5 (Prosser et al. 1991). However, note that the H_α emission of BJJ 358 (a Hyad proper motion member) is stronger than that of the younger Pleiad proper motion member HHJ 10, suggesting that for spectral types later than M5 H_α may not be a good indicator of age. It is also worth recalling that H_α can be highly variable in stars cooler than M5, as observed by us in LHS 2065, and by other authors in different stars (Bessell 1991, Rebolo et al. 1992). It would be desirable to monitor extreme M-stars for variability before trying to use H_α emission as an age indicator. The possibility that H_α emission may sometimes be enhanced due to activity in close binaries should also be checked.

The H_α emission line is the best feature to measure radial velocities in our spectra as it is the only narrow feature present. The procedure to derive the radial velocity was as follows: i) the H_α emission profile was fitted by a gaussian function and the center wavelength was measured; ii) the measured wavelength shifts with respect to the H_α laboratory position were converted into instrumental radial velocities; iii) instrumental radial velocities were checked so that they were all at the same zero-point frame by measuring the positions of ten sky lines in each spectrum; iv) the radial velocities were corrected from diurnal, barycentric and annual velocities to yield heliocentric radial velocities. Despite the fact that H_α emission may form in a region of peculiar kinematics, we assume that the radial velocities derived in this way are good enough, given our rather large uncertainties ($18\text{--}30\text{ km s}^{-1}$). As consistency checks we note that LkCa 21 and V927 Tau had previously published radial velocities of $+6\text{ km s}^{-1}$ and $+19.6\text{ km s}^{-1}$, respectively (Herbig & Bell 1988), which are in good agreement with the velocities obtained by us (Table 2). Stauffer et al. (1994) report a radial velocity of $+2.8 \pm 4\text{ km s}^{-1}$ for HHJ 10, which is consistent with our value of $-3 \pm 18\text{ km s}^{-1}$. Note that LHS 2065 has two very different values for the H_α equivalent width, corresponding to observations made on January 20 and 21, 1993. In spite of the

Table 2: H_α and heliocentric radial velocities

Object	Sp.T.	H_α (\AA)	V_{rad} (km s^{-1})
LkCa 21	M3	5.1	+2
V927 Tau	M5.5	7.2	+21
Sz 81	M5.5	64.6	-21:
HHJ 10	M5.5	5.7	-3
BHJ 358	M6	6.8	+42
LHS 248	M7	6.0	-6
CTI 1156+28	M7	2.7	-19
GL 644 C	M7	5.2	-13:
TVLM 868-110639	M7.5	6.8	-32:
TVLM 513-46546	M8	2.5	+31:
ESO 207-61	M8	1.9	+103:
LHS 2243	M8	1.3	+11
LHS 2397a	M8	22.0	-24:
LHS 2924	M9	1.8	-56
LHS 2065	M9	7.5	+5
		20.3	+4

Notes: The uncertainties in these quantities are the following: spectral type ± 0.4 , H_α equivalent width $\pm 0.5 \text{ \AA}$, and radial velocity $\pm 18 \text{ km s}^{-1}$, except for the values marked with a colon, which have an error bar of $\pm 30 \text{ km s}^{-1}$. The two values of H_α EW and radial velocity for LHS 2065 correspond to observations on two different nights.

large variability of the H_α strength, the radial velocities obtained are the same.

The radial velocities of BHJ 358 and HHJ 10 are consistent within the error bars with those of known members of the Hyades and Pleiades clusters, which are 30-46 km s^{-1} (Kraft 1965) and 0-14 km s^{-1} (Stauffer et al. 1984), respectively. This result reinforces the likelihood of membership to the clusters. It is remarkable that the highest radial velocity in our sample corresponds to ESO 207-61. A high radial velocity is also found for LHS 2924. These high velocities suggest that ESO 207-61 and LHS 2924 may be kinematically old.

c) Search for LiI

We have inspected the data for the presence of the $\text{LiI } \lambda 6707.8 \text{ \AA}$ resonance line but failed to detect it. We are hence only able to place upper limits in our target BD candidates. This can be clearly seen in Figures 1 and 2 where we show the Li region of several programme objects. We checked that we could measure the LiI resonance line of the T Tauri stars LkCa 21, V927 Tau and Sz 81, observed with the same instrumental setups as the programme BD candidates, and obtain the same equivalent widths as measured in high resolution spectra (e.g. Martín et al. 1994). The LiI equivalent widths of these T Tauris range between 750 and 500 mÅ. The 2σ upper limits given in Table 3 were derived considering the strongest possible feature that could be present in the region around $\lambda 6708 \text{ \AA}$, taking into account the S/N ratio and resolution of each spectrum. We note that in three cases we cannot rule out the possibility that there could be weak Li features just at our detection limit (CTI 1156+28, LHS 2397a and TVLM 513-46546). Higher spectral resolution and better S/N spectra are necessary to check if there are weak Li lines in these objects.

The correct method for deriving the effective temperatures of extreme M-type stars remains controversial. For instance, the temperature of an M6 dwarf ranges from 3000 K to 2500 K depending on which calibration is adopted. The effective temperatures listed in Table 3 have been assigned using the spectral types in Table 2 and the calibration of Kirkpatrick et al. (1993), whose work reports the hottest temperatures among all the published T_{eff} conversions. The choice of this warmer temperature scale yields more conservative estimates for the derived upper limits to the abundances, as the LiI line is expected to strengthen by a factor 2-3 from 3000 K to

Table 3: Upper limits to LiI equivalent widths and Li abundances

Object	T_{eff}	LiI (mÅ)	$\log N(\text{Li})$
GL 623 B	3200	<700	<2.0
LHS 1047 B	3200	<500	<1.8
HHJ 10	3120	<300	<1.0
BHJ 358	3030	<300	<-0.2
CTI 1156+28	2940	≤ 400	≤ 0.6
GL 644 C	2940	<200	<-0.3
LHS 248	2940	<170	<-0.4
TVLM 868-110639	2900	<500	<0.5
TVLM 513-46546	2880	≤ 300	≤ -0.1
ESO 207-61	2880	<300	<-0.1
LHS 2397a	2880	≤ 700	≤ 1.0
LHS 2243	2880	<50	<-0.4
LHS 2065	2630	<150	<-1.0
LHS 2924	2630	<250	<-0.8

Note: The upper limits to the equivalent widths listed above have a 90% confidence level.

2500 K (Pavlenko et al. 1994, in preparation).

As argued by Rebolo et al. (1992) and Magazzù et al. (1993), the LiI resonance feature is expected to be quite strong in dwarf atmospheres with $T_{\text{eff}} \sim 2500$ K, and $\log N(\text{Li})$ in the range 3.0-0.0. The presence of a strong LiI doublet in the M6 T Tauri star UX Tau C (Magazzù et al. 1991) proves that Li is easily detectable in late M-type stars when its abundance is high. Furthermore, optical and IR spectra (c.f. Tinney et al. 1993) of the coolest objects in our sample like LHS 2924, show the presence of many strong atomic lines from the neutral alkali elements K and Na, whose atomic structure is similar to Li. Consequently, we attribute non-detections of the LiI resonance feature in terms of physical depletion of the photospheric Li abundance.

We did not resolve the secondaries of GL 623 and LHS 1047, but we estimated the flux of each component around $\lambda 6707 \text{ \AA}$ using the photometric information available, and corrected the equivalent width upper limit from the contribution of the primary. Using the new NLTE curve-of-growth calculations and synthetic profiles presented in Pavlenko et al. (1994, in preparation), we inferred the upper limits to the Li abundances given in Table 3. Pavlenko et al. show that a BD with $T_{\text{eff}}=3000$ K, which has retained its initial Li content of $\log N(\text{Li})=3$, has $\text{EW}(\text{LiI})=2.8 \text{ \AA}$. For temperatures cooler by 500 K their results show that the LiI line is enhanced by about a factor 3. It is clear that such strong lines would be very conspicuous, and easily detectable in our spectra.

4. LITHIUM BURNING AND MASS LOWER LIMITS

The upper limits on the Li abundances of all the BD candidates in our sample are well below $\log N(\text{Li})=3$, which is the cosmic Li value in the solar neighbourhood (e.g. Martín et al. 1994). These limits imply large Li depletions of one or several orders of magnitude. Such an observed depletion constrains the minimum mass of our programme stars. Since our sample of BD candidates is heterogeneous, for clarity we will discuss our results in three independent subsections, as follows:

4.1 Isolated Objects in the Field

An effective way of finding nearby very cool dwarfs has been the photographic surveys of high proper motion stars (e.g. Luyten 1979). We have observed four of the coolest objects known in the LHS catalogue, namely, LHS 2397a, LHS 2243, LHS 2065 and

LHS 2924. They have spectral types in the range M8-M9 V (Kirkpatrick, Henry & Liebert 1993), and LHS 2924 has the lowest luminosity among them (Tinney et al. 1993). Our measurements of a relatively high radial velocity and weak H_α emission suggest that LHS 2924 may be quite old. Its luminosity, lower than that of LHS2065, may not reflect a meager mass, but an older age and lower metallicity.

Bessell (1991) suggested that LHS 2397a, LHS 2065 and LHS 2924 may be as young as a few times 10^8 yr because they have smaller proper motions than bluer stars. While for LHS 2924 our data do not support youth, for the other two stars their strong H_α emission and small radial velocity suggest that they are young. However, it is not clear how H_α could be used as an age indicator as we briefly discussed in Section 3b. Since at present the age of field BD candidates cannot be determined reliably, we will adopt the conservative view that they are old enough to have burnt Li if their masses allow for it. The mass lower limit implied by the observed Li destruction is slightly model-dependent. There are a number of computations, and we find the following lower limits for an age of 10^9 yr: $0.06 M_\odot$ (Magazzù et al. 1993), $0.07 M_\odot$ (Bessell & Stringfellow 1993), $0.065 M_\odot$ (Nelson et al. 1993), $0.065 M_\odot$ (D’Antona & Mazzitelli 1994). If any of these objects happen to be younger than 10^9 yr the mass limit would be shifted to higher masses, but if they were older the mass limit would not change.

The theoretical cooling track of a $0.06 M_\odot$ BD runs very close and almost parallel to the faint end of the main sequence (MS) during several times 10^7 yr. Given the large uncertainties in effective temperature, the position of isolated field BD candidates in the H-R diagram is a poor indicator of mass and age, and cannot distinguish between very low mass stars and young BDs. This is illustrated in Fig. 3 where we show the MS (isochrone of age 10^{10} yr for masses larger than $0.076 M_\odot$) and cooling tracks of Burrows et al. (1993), corresponding to their model X, and we also mark the “Substellar Lithium Region” (SLR). We define such a region as that occupied by objects whose mass is low enough for Li to be preserved with an abundance $\log N(\text{Li}) \geq 2.0$, i.e. the depletion is less than a factor 10. In Fig. 3 we have only shadowed the SLR for ages older than 3×10^6 yr because Burrows et al. 1993 do not give younger isochrones. For the purpose of our study it is relevant to remark that at ages younger than about 10^8 yr the SLR includes all the substellar domain, but for older ages it is restricted to masses below $0.065 M_\odot$.

The BD candidates of our sample in common with Tinney et al. (1993) are plotted in Fig. 3, denoted by crosses, using the luminosities and temperatures given by those authors. It is clear that the position of these objects in the SLR is incompatible with the Li destruction inferred from our observations. This problem can be solved if we shift the objects towards higher effective temperatures. We plotted in the Figure (open pentagons) the same objects but using temperatures estimated from the calibration of Kirkpatrick et al. (1993) (see Table 3). In this case the points lie below the MS, and thus this calibration gives excessively hot temperatures. The temperature calibration that would best fit the constraints of Li depletion and theoretical tracks in the H-R diagram is intermediate between the one adopted by Tinney et al. (1993) and Kirkpatrick's et al. (1993). We have also tested the parameters given by Bessell & Stringfellow (1993) for the faintest dwarfs. Their objects in common with our sample are plotted as black squares in Fig. 3, and we see that the agreement is better. Only one object (LHS 248) out of seven lies in the forbidden SLR, and some of them overlap with the predicted position of the MS for masses 0.09-0.08 M_{\odot} . One of the objects (ESO 207-61) has a luminosity grossly displaced below the MS, but this may be due to low metallicity. We conclude that the temperature calibration adopted by Bessell & Stringfellow (1993), which is essentially Bessell's (1991), gives in general positions in the H-R diagram roughly consistent with the standard tracks of Burrows et al. (1993), and satisfying the constraint imposed by the Li test that they cannot be in the SLR since they do not exhibit any lithium. An important consequence is that none of the fields BD candidates in Fig. 3 is a contracting very young substellar object. Nevertheless, it is not discarded that they may be BDs with masses in the range 0.08-0.065 M_{\odot} and ages between 10^8 yr and 10^9 yr. Objects of such masses and ages are capable of efficiently destroying Li and yet they will fail to settle on the main sequence.

4.2 Objects in Binary Systems

Very low mass stars in binary systems allow the possibility of obtaining dynamical information on their masses. The lowest mass eclipsing binary known to date is CM Dra (GL 630.1), which is composed of two M4.5 dwarfs of masses 0.237 M_{\odot} and 0.207 M_{\odot} (Lacy 1977). Unfortunately no eclipsing binary system with lower mass dwarfs has ever been discovered. Other binary systems have dynamical mass measurements of considerably lower accuracy. Therefore, the application of the Li test

sheds light on the masses of the components.

Magazzù et al. (1993) applied the Li test to the binary systems Wolf 424 (GL 473) and Ross 614 (GL 234), and described how non-detection of Li constrains the mass range allowed by the orbital error bars. In this paper we present similar results on GL 623 and LHS 1047. The first one has two independent estimates of the secondary dynamical mass; $0.067\text{--}0.087\text{ M}_\odot$ (Marcy & Moore 1989), and $0.114\pm0.042\text{ M}_\odot$ (Henry & McCarthy 1993). The Li depletion inferred by us supports that the mass of GL 623B is larger than 0.065 M_\odot .

The dynamical mass of LHS 1047B is poorly determined; Ianna, Rohde & McCarthy (1988) obtained $0.055\pm0.032\text{ M}_\odot$, and Henry & McCarthy (1993) note that the uncertainties are much larger than $\pm0.032\text{ M}_\odot$. The Li non-detection implies that the mass is larger than 0.065 M_\odot , and hence it constraints the range of masses allowed by the error bar. We note that the results of the Li test for these binaries and those reported by Magazzù et al. (1993) are consistent with the finding of Kirkpatrick & McCarthy (1994) that the secondaries of Ross 614 and LHS 1047 have spectral types no later than M6.5 V.

4.3 Isolated Objects in Open Clusters

Several searches for substellar objects in nearby open clusters have been carried out in the last few years (e.g. Stauffer et al. 1989, Bryja et al. 1994). Dozens of BD candidates were identified on the basis of very red optical or IR colours, but for only very few of them do proper motion and spectroscopic studies exist. We have chosen to apply the Li test to one of the reddest proper motion members known in the Pleiades (HHJ 10, Hambly et al. 1993), and the faintest proper motion Hyades member in the sample of Bryja et al. (1994). Our analysis of spectral types, H_α emission and radial velocity presented in Section 3 confirm that HHJ 10 and BHJ 358 are *bona-fide* members of these clusters.

The Li test provides stronger mass constraints in Pleiades stars than in Hyades stars because of the difference in ages of about a factor ten. The SLR has an upper mass limit of 0.08 M_\odot or higher for ages lower than about 10^8 yr , while for ages of a few $\times 10^8\text{ yr}$ the upper mass limit is $\sim 0.065\text{ M}_\odot$. In Figure 4 we compare the H-R diagram position of HHJ 10 with the theoretical models of Burrows et al. (1993). We have used

the photometric data in Steele, Jameson & Hambly (1993) and the conversions from I-K colour to BC and T_{eff} of Bessell (1991). It is clear that HHJ 10 is inside the SLR, and the tracks indicate a mass of about $0.055 M_{\odot}$. This is obviously inconsistent with the large Li depletion observed.

Very recently Marcy, Basri & Graham (1994) applied the Li test to two other Pleiad BD candidates; HHJ 3 and HHJ 14. The first is about half a magnitude fainter in I than HHJ 10, and the second is slightly brighter, but all three have the same colour (I-K)=3.3 (Steele et al. 1993). Just one spectral type is available, which is M5.6 for HHJ 10 as derived by us using the scale of Kirkpatrick et al. (1991). Marcy et al. (1994) report Li non-detections in their spectra, which have considerably higher resolution than but similar S/N ratio as ours.

As we pointed out before, the Li test does not confirm the substellar mass implied by the position in the H-R diagram of HHJ 10. In Figure 4 we plot HHJ 3 and HHJ 14 in the H-R diagram and we see that they lie in the SLR as well. In order to bring the positions of these stars outside the SLR, they would have to be shifted by 200 K to hotter T_{eff} . Current uncertainties in assigning temperatures to these objects could allow for such an effect. In particular Steele et al. (1993) have noted that the (R-I) vs. (I-K) relationship for very low mass Pleiades stars seems to be different than that of field dwarfs. We note that our spectral type for HHJ 10 of about M5.5 is more in agreement with its (R-I) colour of 1.9 (Steele et al. 1993) than with its (I-K) of 3.3. Use of (R-I) for deriving a T_{eff} gives a value of 3000 K, which is a little more than 200 K hotter than the T_{eff} derived from (I-K). Because the spectral type and (R-I) colour imply a T_{eff} hot enough to explain the Li burning, this suggests that the (I-K) colour for very low mass Pleiades stars may be systematically redder than for field stars. Such an effect may be caused by a near-IR excess in these young objects, or anomalous extinction, or perhaps a peculiar molecular band pattern. Spectroscopic observations in the optical and the IR are encouraged to establish the cause of this colour anomaly.

On the other hand it is worth recalling that the theoretical PMS tracks are quite uncertain. For instance, D'Antona & Mazzitelli (1994) have discussed to some extent the influence of different opacities and treatments of convection. In particular, we note that their new tracks with the Canuto-Mazzitelli convection treatment, are hotter by

about 180 K at $0.08 M_{\odot}$, and age 7×10^7 yr, than model X of Burrows et al. (1993). Therefore, at the age of the Pleiades the SLR based on D’Antona & Mazzitelli’s models is shifted towards hotter temperatures and hence it is more difficult to explain the observed Li depletion in our BD candidates.

The discrepancy between the Li test and the masses implied by the PMS models may be a consequence of assigning too low T_{eff} to very low mass Pleiades stars, and/or that the tracks predict temperatures that are too hot for young substellar objects. From the considerations given above about the (I-K) colours of Pleiades BD candidates, we favour the hypothesis that the temperatures of HHJ 3, 10 and 14 are higher by about 200 K than previously thought. It is necessary to derive reliable T_{eff} for the lowest mass Pleiades stars in order to test theoretical evolutionary models.

With respect to the Hyad BD candidates, we consider the cases of BHJ 358 and ESO 207-61. The latter object is possibly a member of the Hyades moving group according to Ruiz et al. (1991). However, our radial velocity is very high and the luminosity given by Bessell & Stringfellow (1993) is very low, and therefore its connection to the Hyades seems unlikely. Thus, we have plotted only the position of BHJ 358 in Figure 4 using the photometry given by Bryja et al. (1994) and the calibrations of Bessell (1991). It can be seen that BHJ 358 lies just outside the SLR. We can only impose a lower limit of $0.065 M_{\odot}$ from the observed Li depletion which is consistent with the theoretical mass of $\sim 0.08 M_{\odot}$ inferred from its position on the H-R diagram.

5. CONCLUSIONS

The central conclusion of this paper is that Li has not been detected in intermediate resolution spectra of 14 BD candidates. We estimate minimum Li depletions in these objects ranging from a factor of 10 for GL 623 B to a factor of 10^4 for LHS 2065 and LHS 2924. The fact that Li has been efficiently burnt implies that the masses are greater than $0.065 \pm 0.005 M_{\odot}$.

Our data support membership of HHJ 10 and BHJ 358 to the Pleiades and Hyades clusters, respectively, because of their late spectral type, H_{α} emission and consistent radial velocities. The non Li detections imply masses $> 0.08 M_{\odot}$ for the Pleiades member and $> 0.065 M_{\odot}$ for the older Hyades member.

In order to illustrate the implications of the Li test in the H-R diagram we have defined the Substellar Lithium Region (SLR). The BD candidates are located inside or outside the SLR depending on the temperatures adopted for them. Since the observed Li depletions prevent these objects from being inside the SLR we conclude that some temperature calibrations give excessively low values of T_{eff} . Only a narrow region in the H-R diagram, between the SLR and the main sequence, is allowed for our sample of very low mass dwarfs, and the temperature calibrations should satisfy these constraints.

At ages younger than about 10^8 yr the SLR comprises all the substellar domain. Thus, young objects, like the Pleiades members, that have burnt their Li are not brown dwarfs. Adopting the frequently used (I-K) vs. T_{eff} calibration for the faintest proper motion Pleiades members currently known, leads to the inconsistent result that they lie well inside the SLR in the H-R diagram. We argue that this inconsistency could be solved if these stars are about 200 K hotter than inferred from their (I-K) colours. The (R-I) colour and the spectral type of HHJ 10 suggest that such a hotter temperature may be correct. Further considerations on the validity of theoretical evolutionary tracks and isochrones have to be postponed until a reliable temperature scale is established for the very low mass Pleiades objects.

ACKNOWLEDGEMENTS

Drs. F. Allard, G. Basri, C. Bryja, F. D'Antona, N.C. Hambly, T.J. Henry, R.F. Jameson, J.D. Kirkpatrick, G.W. Marcy, C.F. Prosser, J. Stauffer and C.G. Tinney are gratefully acknowledged for communicating results prior to publication. We thank J.A. de Diego for his kind help with the English, and the referee (J.D Kirkpatrick) for many comments that helped us to improve this paper. This work has been partially supported by the Spanish DGICYT project No. PB92-0434-C02.

References

- Bessell, M.S. 1991, *AJ*, 101, 662
- Bessell, M.S. & Stringfellow, G.S. 1993, *ARAA*, 31, 433
- Bryja, C., Humphreys, R.M. & Jones, T.J. 1994, *AJ*, 107, 246
- Burrows, A., Hubbard, W.B., Saumon, D. & Lunine, J.I. 1993, *ApJ*, 406, 158
- D’Antona, F. & Mazzitelli, I. 1994, *ApJS*, 90, 467
- Hambly, N.C., Hawkins, M.R.S. & Jameson, R.F. 1993, *A&AS*, 100, 607
- Henry, T.J. & McCarthy, Jr., D.W. 1993, *A.J.*, 106, 773
- Herbig, G.H. & Bell, K.R. 1988, *Lick Obs. Bull.*, No. 1111
- Ianna, P.A. 1993, in “Developments in Astrometry and their Impact on Astrophysics and Geodynamics”, p. 75
- Ianna, P.A., Rohde, J.R. & McCarthy, D.W. 1988, *AJ*, 95, 1226
- Kirkpatrick, J.D. & McCarthy, Jr, D.W. 1994, *AJ*, 107, 333
- Kirkpatrick, J.D, Henry, T.J. & McCarthy, Jr., D.W. 1991, *ApJS*, 77, 417
- Kirkpatrick, J.D, Kelly, D.M., Rieke, G.H., Liebert, J., Allard, F. & Wehrse, R. 1993, *ApJ*, 402, 643
- Kirkpatrick, J.D, McGraw, J.T., Hess, T.R., Liebert, J., & McCarthy, Jr, D.W. 1994, *ApJS*, in press
- Kraft, R.P. 1965, *ApJ*, 142, 681
- Lacy, C. 1977, *ApJ*, 218, 444
- Leggett, S.K. 1992, *ApJS*, 82, 351

- Luyten, W.J. 1979, LHS Catalogue, Minneapolis, Univ. of Minnesota
- Magazzù, A., Martín, E.L. & Rebolo, R. 1991, *A&A*, 249, 149
- Magazzù, A., Martín, E.L. & Rebolo, R. 1993, *ApJ*, 404, L17
- Marcy, G.W. & Moore, D. 1989, *ApJ*, 341, 961
- Marcy, G.W., Basri, G., & Graham, J.R. 1994, *ApJ*, in press
- Martín, E.L. 1993, PhD Thesis, Universidad de La Laguna
- Martín, E.L., Rebolo, R., Magazzù, A. & Pavlenko, Ya.V. 1994, *A&A*, 282, 503
- Nelson, L.A., Rappaport, S. & Chiang, E. 1993, *ApJ*, 413, 364
- Prosser, C.F., Stauffer, J. & Kraft, R.P. 1991, *AJ*, 101, 1361
- Rebolo, R. 1991, in “Evolution of Stars: The Photospheric Abundance Connection”, IAU Symp. 145, eds G. Michaud & A. Tutukov, Kluwer, p. 85
- Rebolo, R., Martín, E.L. & Magazzù, A. 1992, *ApJ*, 389, L83
- Rebolo, R., Martín, E.L. & Magazzù, A. 1994, in 8th Cambridge workshop on Cool Stars, Stellar Systems and the Sun, ed J.-P. Caillault, *PASP Conf. Series*.
- Ruiz, M.T., Takamiya, M.Y. & Roth, M. 1991, *ApJ*, 367, L59
- Stauffer, J., Hartmann, L.W., Soderblom, D.R. & Burham, J.N. 1984, *ApJ*, 280, 202
- Stauffer, J., Hamilton, D., Probst, R., Rieke, G. & Mateo, M. 1989, *ApJ*, 344, L21
- Stauffer, J., Liebert, J., Giampapa, M., Macintosh, B., Reid, N. & Hamilton, D., 1994, *AJ*, in press
- Steele, I.A., Jameson, R.F. & Hambly, N.C. 1993, *MNRAS*, 263, 647
- Tinney, C.G., Mould, J.R. & Reid, I.N. 1993, *AJ*, 105, 1045

Figure Captions:

Figure 1. Final spectra of five programme stars from Table 1. The left panel displays a wide spectral range, and the right panel shows a zoom of the region around the LiI $\lambda 6707.8\text{\AA}$ resonance line. Fluxes are relative, with the pseudo-continuum at $\lambda 6700\text{\AA}$ taking a value of unity. The resolutions are between FWHM= 1.4 and 4.4\AA (see Table 1). A box-car smoothing of width 2 pixels has been applied. The top spectrum is that of a T Tauri star, showing a strong LiI resonance line of EW=715 mÅ (Martín et al. 1994). In contrast, the other spectra do not present detectable LiI lines.

Figure 2. Final spectra of another five programme stars from Table 1. This Figure is organized in the same way as the previous one. Note the presence of a weak feature in CTI 1156+28 near the expected position for the LiI line.

Figure 3. Our sample of field BD candidates in the H-R diagram. Crosses denote stars in common with Tinney et al. (1993), plotted using the luminosities and temperatures reported by them. Open pentagons are the same objects and luminosities but the temperatures are obtained from the calibration of Kirkpatrick et al. (1993). Black squares are our stars in common with Bessell & Stringfellow (1993), using the parameters given by them. For comparison with theoretical computations we have superimposed the tracks of Burrows et al. (1993) for masses of 0.1, 0.08 and $0.06 M_{\odot}$ (dashed lines), and we have also drawn their isochrones for 3×10^6 yr and 10^{10} yr (solid lines). The Substellar Li region defined in the text is marked with slanting lines.

Figure 4. Faint proper motion cluster members in the H-R diagram. We plot the Pleiades stars HHJ 3, 10 and 14 as asterisks, and the Hyades star BHI 358 as an open polygon. The tracks and SLR are the same as in the previous Figure. We have superimposed the isochrones from Burrows et al. 1993 for 70 Myr (Pleiades age) and 600 Myr (Hyades age). Note that all three Pleiades BD candidates fall inside the SLR and above the 70 Myr isochrone.

This figure "fig1-1.png" is available in "png" format from:

<http://arXiv.org/ps/astro-ph/9406017v1>

This figure "fig1-2.png" is available in "png" format from:

<http://arXiv.org/ps/astro-ph/9406017v1>

This figure "fig1-3.png" is available in "png" format from:

<http://arXiv.org/ps/astro-ph/9406017v1>

This figure "fig1-4.png" is available in "png" format from:

<http://arXiv.org/ps/astro-ph/9406017v1>